THE INFLUENCE OF BIODYNAMIC FEEDTHROUGH ON HANDLING QUALITIES

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Abstract

This paper presents a new concept on pilot model that allows the study of handling qualities and PIO (Pilot-Induced Oscillations) of elastic aircraft since it computes not only the voluntary pilot inputs in order to accomplish a given task, but also the involuntary commands due to the biodynamic feedthrough (BDFT) or Pilot-Assisted Oscillations (PAO) phenomena. Frequency-domain criteria used for PIO prediction are analyzed and pilot simulations are also presented.

1 Introduction

Mathematical models to describe the human pilot have been widely explored over the recent past decades with the purpose of handling qualities and PIO analysis. Since aircraft's dynamic response depends on pilot's actions, and that pilot's actions upon an aircraft also depend on the dynamics response of the latter, it can be said that both pilot and aircraft form a feedback closed-loop system called the Pilot-Vehicle System (PVS) as depicted in Fig. 1. Pilot can then be understood as a controller.

Among the various models developed until now, it's worth mentioning the structural model developed by Hess [1] or the optimal control model proposed by Kleinman et al [2]. For the study proposed in this paper, we considered the compensatory pilot model described by McRuer [3], due to it's simplicity. Pilot model can then be described by the transfer function of equation 1, considering as input the error to be minimized and as output the amount of control inceptor displacement necessary. Transfer function is composed of a gain K_{pilot}, an effective time delay $e^{-\tau_h s}$ and a zero correspondent to the term $(T_{Lead}s+1)$, which is an anticipation factor used by the pilot in order to compensate aircraft's deficiencies in order to accomplish the task.

$$Y_{pilot}(s) = K_{pilot}e^{-\tau_h s}(T_{Lead}s+1)E(s) \qquad (1)$$

Structural dynamics of aircraft is responsible for vibrations in the whole airframe, and especially in the cockpit. Those vibrations may degrade the performance of a human pilot in accomplishing a given task by introducing undesired involuntary sidestick inputs to the aircraft. This phenomena is known as the biodynamic feedthrough effect, and is considered to be the reason for a specific kind of PIO called PAO, acronym for Pilot Assisted (or Augmented) Oscillation. Walden [4] and Muscarello et al. [5] argued that PAO is more common on rotary-wing aircraft. Regarding fixed-wing aircraft, Magdaleno et al. [6] exposed that flexibility may add further lags to rigid body modes and contribute to the development of linear PIO. Raney and Schmidt [7] and Damveld [8] also showed how flexibility could impact handling qualities.

In this context, Allen [9] introduced a model that considers the pilot as a passive spring-mass-damper second order dynamic system that receives as input the cockpit vibration and calculates as output the involuntary stick commands, according to the transfer function depicted in Eq. 2. The work also details the human body reso-

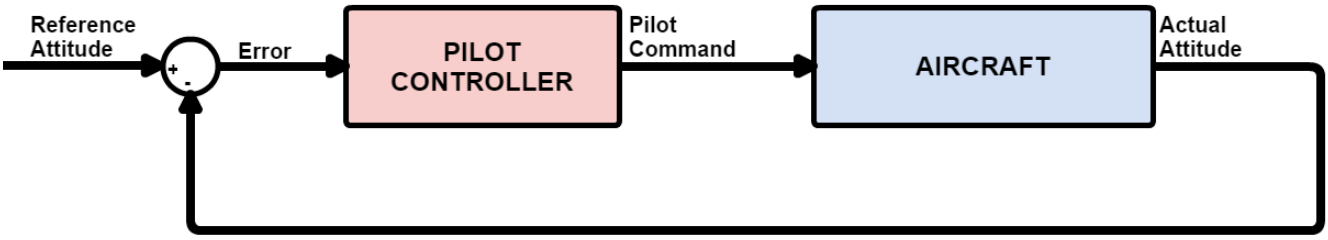

Fig. 1 Pilot-Vehicle System with pilot using compensatory behavior.

nances due to longitudinal load factor, such as pilot's shoulder that could impact the efficiency of the capture task by introducing involuntary stick commands and also the resonance of pilot's head that causes the effect of visual blurring, which means that pilot would find some difficulty in following the indications shown at the displays.

$$G_{BDFT}(s) = \frac{\delta_{stick}}{n_z} = \frac{2260}{s^2 + 22.62s + 1560} \qquad (2)$$

The present study introduces then a mixed pilot model, according to block diagram presented in Fig. 2. Overall stick command can be calculated by summing both voluntary and involuntary pilot commands as shown on Eq. 3. Voluntary pilot inputs are modelled by a compensatory pilot model $Y_P(s)$ and acts as a controller following a given reference by minimizing the error $E(s)$. Involuntary pilot inputs are summed as a disturbance, and are given by biodynamic feedthrough transfer functions $G_{BDFT}(s)$ and cockpit vibration represented by load factor n_z. Important to mention that this model consider only the effects of cockpit vibration into involuntary pilot commands, but do not contemplate other effects such as visual blurring, which could also affect pilot control strategy.

Also interesting to mention the work developed by Venrooij et al [10], in which it is demonstrated that biodynamic feedthrough depends on how hard the pilot holds the stick. The result also corroborates with pilot reports it which some instabilities were faced when flying in turbulence, and how these instabilities increased as pilots tried to hold harder on the commands.

Another important contribution on handling qualities of flexible aircraft was placed by Adams et al. [11], in which pilot evaluation scales considering cockpit vibration are proposed, similar to the Cooper-Harper rating scale [12]. Two 6-point scales are proposed: the RQR (Ride Qualities Rating) which evaluates how cockpit vibration can degrade handling qualities, and CIR (Control Input Rating) which evaluates if cockpit vibration introduces undesired pilot commands. If in a given experiment pilot rates as 1 both RQR and CIR scales and gives a poorer rating on the Cooper-Harper scale, it means that the degradation on handling qualities is not due to cockpit vibration.

$$\delta_{stick} = Y_P(s)E(s) + G_{BDFT}(s)n_z \qquad (3)$$

As already demonstrated on previous reserach [15], increasing aircraft flexibility may degrade handling qualities. The present work then proposes to investigate how the presence of biodynamic feedthrough can affect PIO analysis with pilot models proposed for the longitudinal dynamics. In order to do so, frequency-domain criteria for PIO prediction will be studied such as the Bandwidth versus Phase Delay presented by Mitchel and Hoh [13] and the Gibson's criterion [14]. Results of pilot simulations will also be presented.

2 Aircraft Model

In order to investigate the effect of the biodynamic feedthrough coupled with flexible aircraft dynamics, the GNBA model proposed by Guimarães Neto [16] will be used. This model was defined in the state-space form described below, considering the six-degree-of-freedom aircraft motion represented in the rigid states x_R and

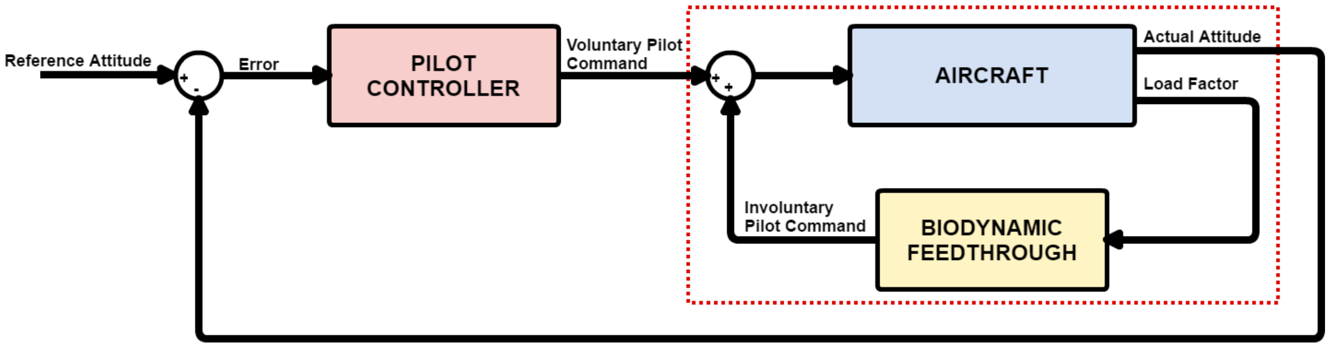

Fig. 2 Pilot-Vehicle System with Biodynamic Feedthrough.

the elastic modes with amplitudes η_i up to 25 Hz in frequnecy represented in the elastic states x_F. In addition, a set of aerodynamic lag states that represent the effects of flow unsteadiness [16] is included.

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx + Du \end{aligned} \tag{4}$$

$$x = \begin{bmatrix} x_R & x_F \end{bmatrix}^T \tag{5}$$

$$x_R = \begin{bmatrix} V & \alpha & q & \theta & H & X & \beta & \phi & p & r & \psi & Y \end{bmatrix}^T \tag{6}$$

$$x_F = \begin{bmatrix} \eta_i & \dot{\eta}_i & \eta_{lag} \end{bmatrix}^T \tag{7}$$

$$u = \begin{bmatrix} i_H & \delta_{elev} & \delta_{ail} & \delta_{rud} & \delta_{throttle} \end{bmatrix}^T \tag{8}$$

For this handling qualities analysis, two different kinds of aircraft models will be considered for each elasticity level (except for the Rigid Body one). First set includes the aeroelastically quasistatic models, which is the current practice on aircraft industry. These models consider static elastic corrections on aerodynamic coefficients. On the other hand, second set of models consider methodology proposed by Waszak and Schmidt at [17], which introduces two dynamic states for each vibration mode that are represented by η_i and $\dot{\eta}_i$. From now on, this formulation will be called simply as flexible (or flex) formulation, while quasistatic formulation will be denoted as QS.

3 Frequency-domain Criteria Analysis

A first glance at the effects of biodynamic feedthrough inclusion upon handling qualities can be made by looking at some of the several criteria specified over the years to analyze PIO prediction and prevention. These criteria consider only the aircraft dynamics, disregarding pilot models. The purpose of analyzing frequency-domain criteria is to verify how the biodynamic feedthrough model could impact handling qualities analysis, by considering both aircraft and BDFT model as a closed-loop model.

The analysis herein presented consider only the open-loop aircraft dynamics. Notch filters used to decouple rigid and elastic modes are not accounted for, since for more flexible aircraft their implementation can bring additional phase lags up to prohibitive levels as demonstrated in [18].

Figure 3 exposes the results for the Bandwidth versus Phase Delay criterion. It can be seen that the introduction of the BDFT model slightly decreases the bandwidth and increases the phase delay for all elasticity levels and for both flexibility formulations. This increase in phase delay, although not significant in absolute values, is enough for the flexible models to fall into the region susceptible to PIO, since they present phase delay higher than 0.15s. However, this value is only a reference and not a strict pass-fail criterion.

For what concerns Gibson's criterion, it can be concluded from Fig. 4 that the inclusion

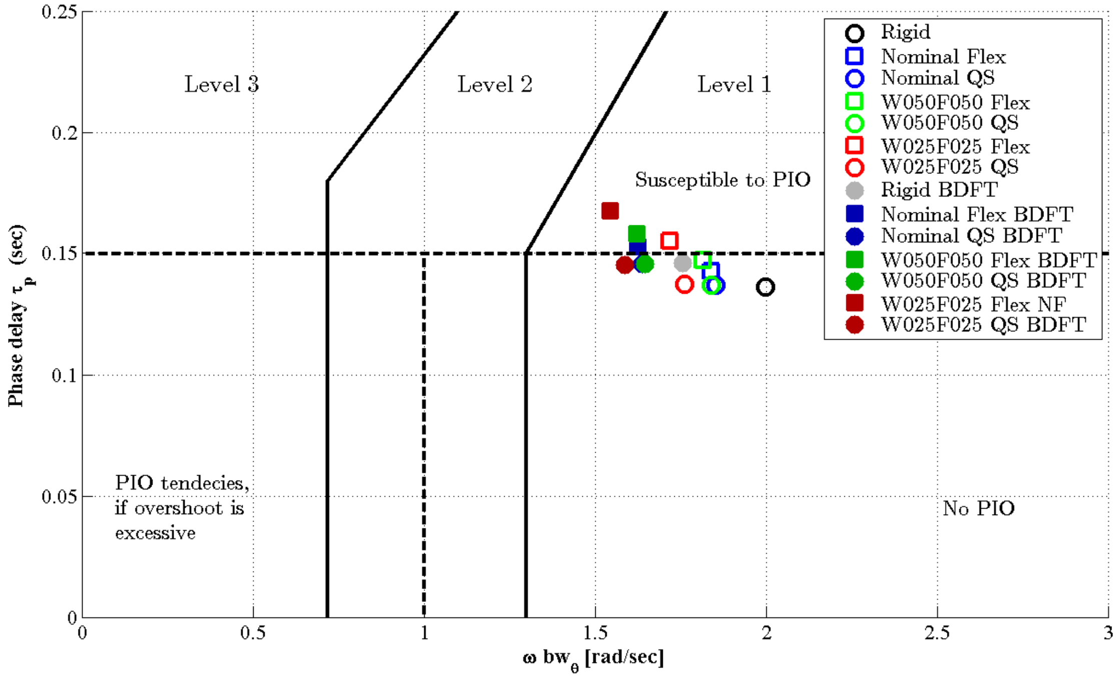

Fig. 3 Bandwidth versus Phase Delay criterion with Biodynamic Feedthrough inclusion.

of biodynamic feedthrough model decreases the phase margin of the analyzed models. Nevertheless, the impact is very small since there is little difference between models that include the biodynamic feedthrough and the ones that do not take it into account.

Most interesting result is that there is much difference between models that consider quasistatic and flexible formulation. Quasistatic models present almost the same result for all elasticity levels, while flexible models show degradation on handling qualities levels as elasticity increases. This degradation occurs due to the presence of the flexible modes on the magnitude curves of the frequency response.

It must be emphasized that the frequency domain criteria should only be used as guidelines for handling qualities analysis, and not strict pass/fail criteria. In order to have a better understanding of the impact of the biodynamic feedthrough models, pilot-in-the-loop simulations are necessary.

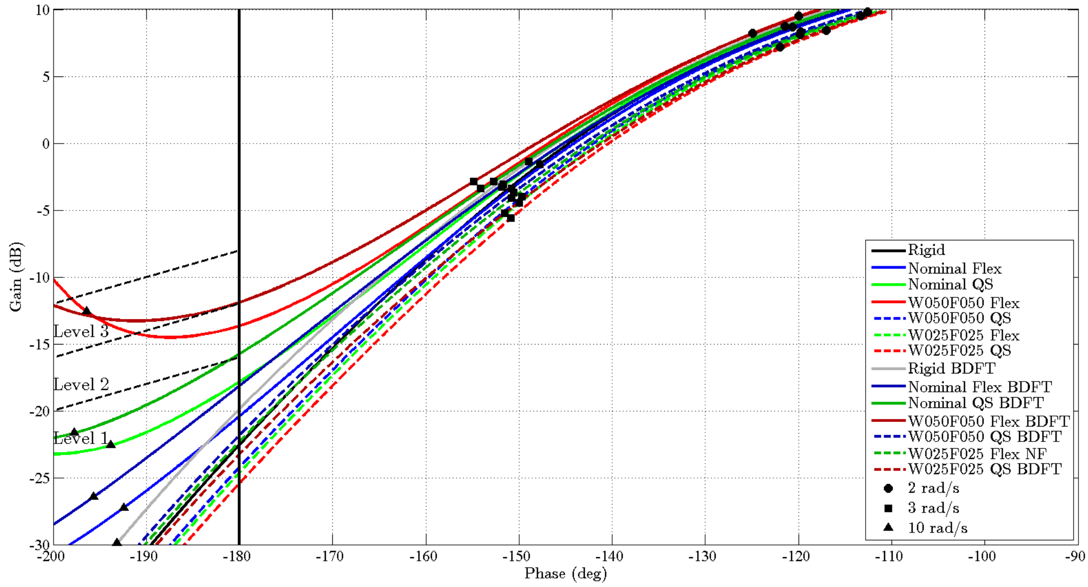

Fig. 4 Gibson's criterion with Biodynamic Feedthrough inclusion.

4 Pilot-in-the-loop Simulations

For the simulations proposed, it is considered the pitch capture maneuver, described in AC 25-7C [19], and which is widely used for certification of current transport aircraft. In this maneuver, pilot attempts to stabilize the aircraft in a pitch angle 5 degrees higher than the initial value.

For the voluntary pilot commands, it is considered a compensatory pilot model with the following parameters: $K_{pilot} = 1$, $T_{Lead} = 0.5$s and $-\tau_h = 0.3$s.

Figure 5 presents the results for the simulation in which the biodynamic feedthrough model is disregarded. It can be seen that as flexibility increases, there is a tendency for higher frequency oscillations. This result indicates that in a maneuver used to evaluate PIO by inserting high frequency pilot inputs, some flexible modes can be assessed and therefore interfere in the precision of task accomplishment. This result can only be seen on flexible models, but not in quasistatic ones.

From Fig. 6, which presents the power-spectral density (PSD) of the pitch rate in the cockpit signal, it can be seen a higher intensity peak in a frequency close to the short-period one and another smaller peak in the frequency of the first flexible mode. This peak is present only on the flexible formulation, and it is noticeably higher for the more flexible configuration W025F025, since it has the smallest frequency for the first elastic mode.

Finally, it can be concluded that Gibson's criterion was able to capture this result, since it predicted a degradation on handling qualities level for the more flexible modes, while the Bandwidth versus Phase Delay criterion did not.

The inclusion of the biodynamic feedthrough model can be analyzed on Fig. 7, that shows that pitch capture simulation when this effect is included. A high frequency oscillation is observed, as in Fig. 5. However, this oscillation is in a frequency higher than the one observed in the previous simulation, and this time divergent, indicating that the system pilot-aircraft is unstable.

Figure 8 shows the PSD of the pitch rate in the cockpit for this simulation. Another higher frequency peak close to the peak of an aeroelastic mode can be observed, corresponding to the human pilot body resonance. A coupling of these two frequencies led to a divergent PIO. Looking

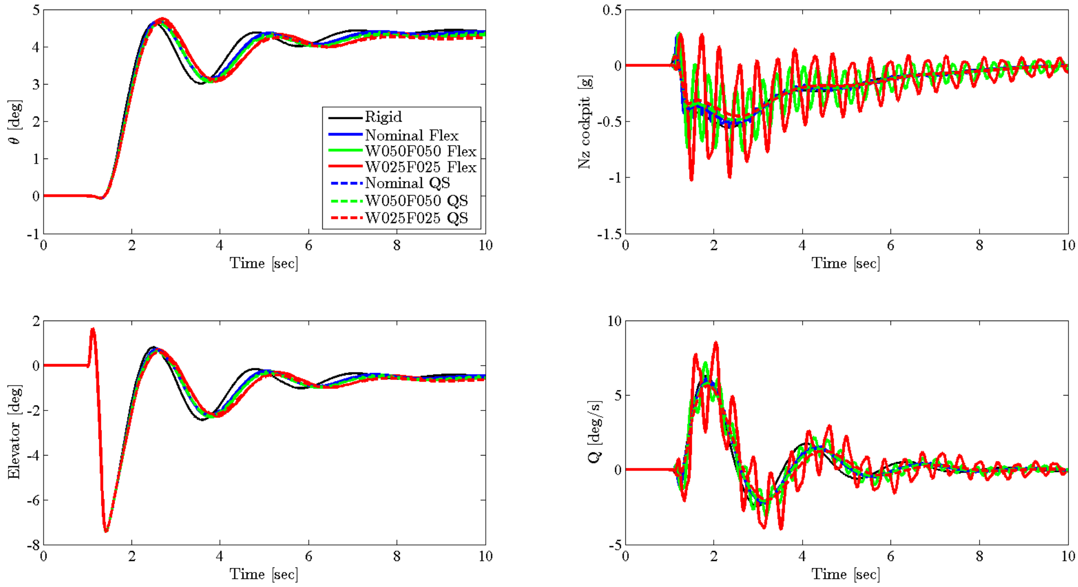

Fig. 5 Pitch capture simulation, biodynamic feedthrough model not included.

to Fig. 9, where pilot commands during the pitch-capture task are decomposed into voluntary and involuntary commands, it becomes clear that the observed unstable oscillation is a direct result of adding the biodynamic feedthrough effect.

It is worth to mention that neither Bandwidth versus Phase Delay nor Gibson's criteria were able to predict such instability. In fact, these criteria were established in order to predict PIO, while the phenomenon observed in the simulation is clearly a PAO. If this experiment was rated by a real pilot, he/she would probably rate it as 6 (most unfavorable rate) on both RQR and CIR scales introduced by Adams et al. [11].

Although PAO is also a phenomenon caused by an instability in a control loop involving both pilot and the aircraft, it follows a dynamic completely different from the classical PVS system presented in Fig. 1. It is then not surprising that the frequency-domain criteria failed to predict this result.

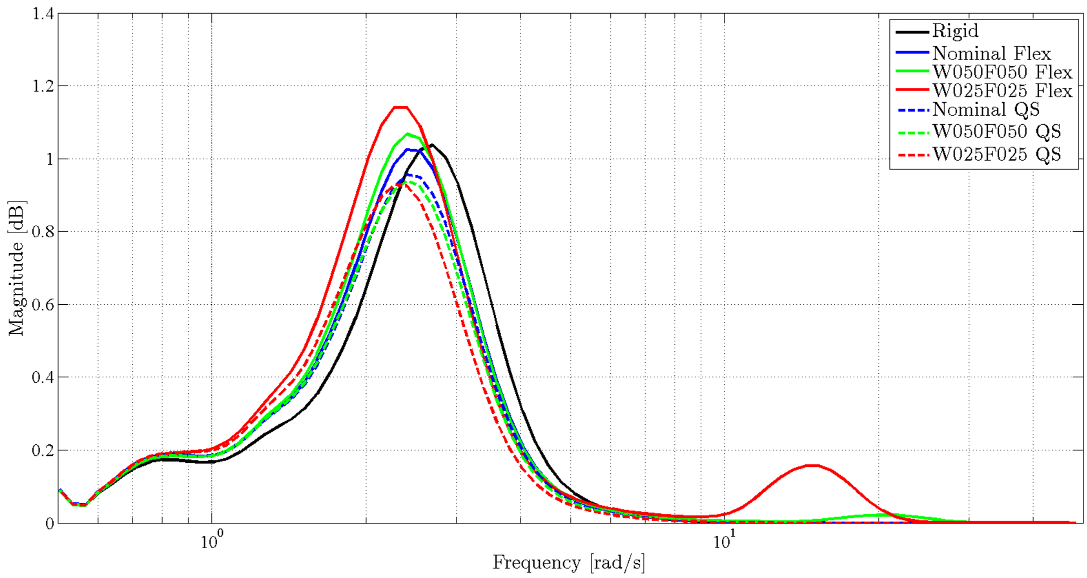

Fig. 6 Power-spectral density, biodynamic feedthrough model not included.

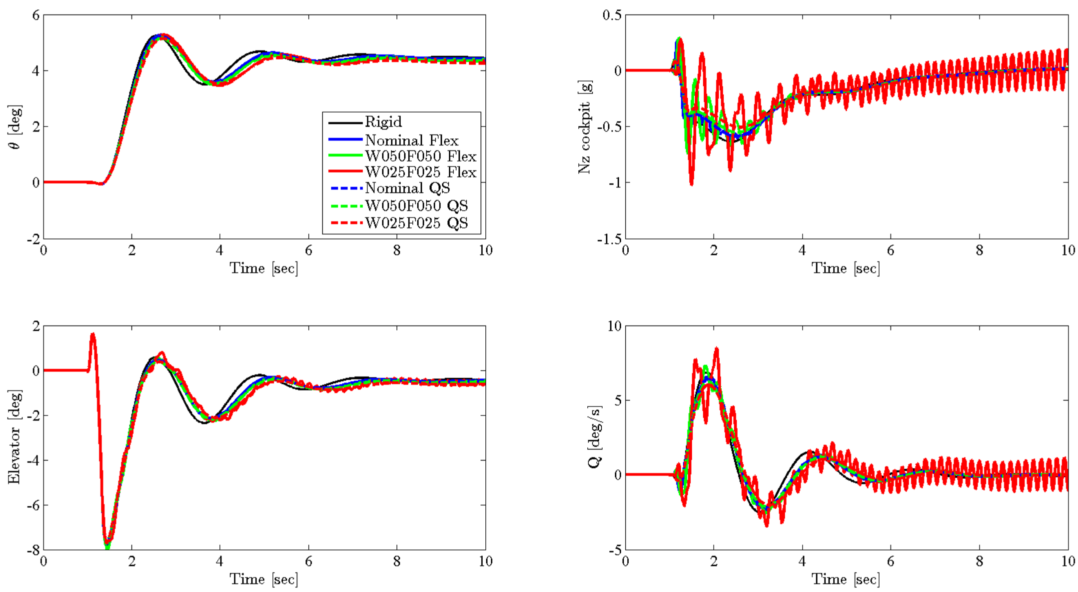

Fig. 7 Pitch capture simulation, biodynamic feedthrough model included.

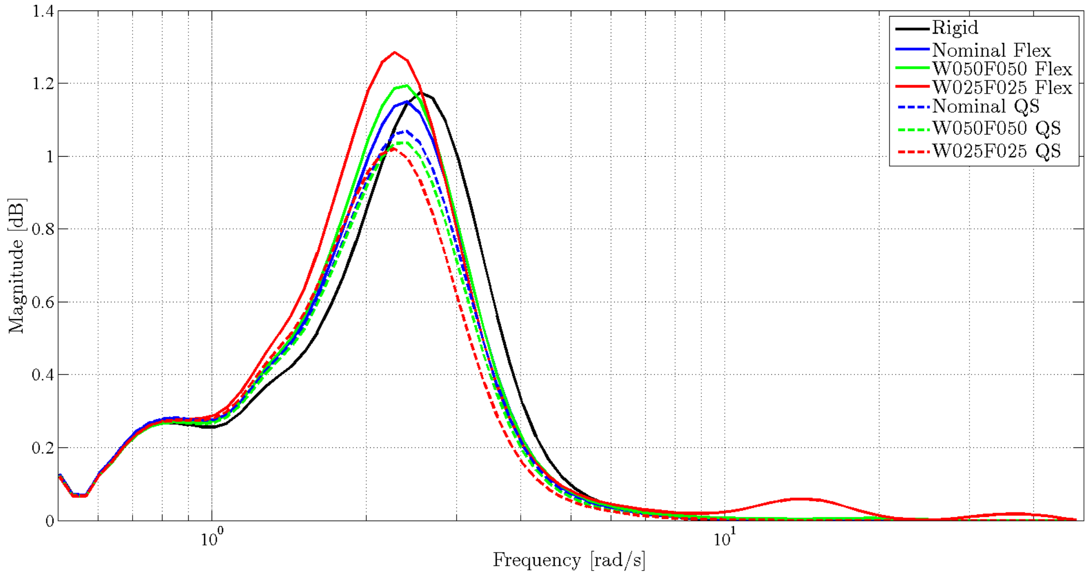

Fig. 8 Power-spectral density, biodynamic feedthrough model included.

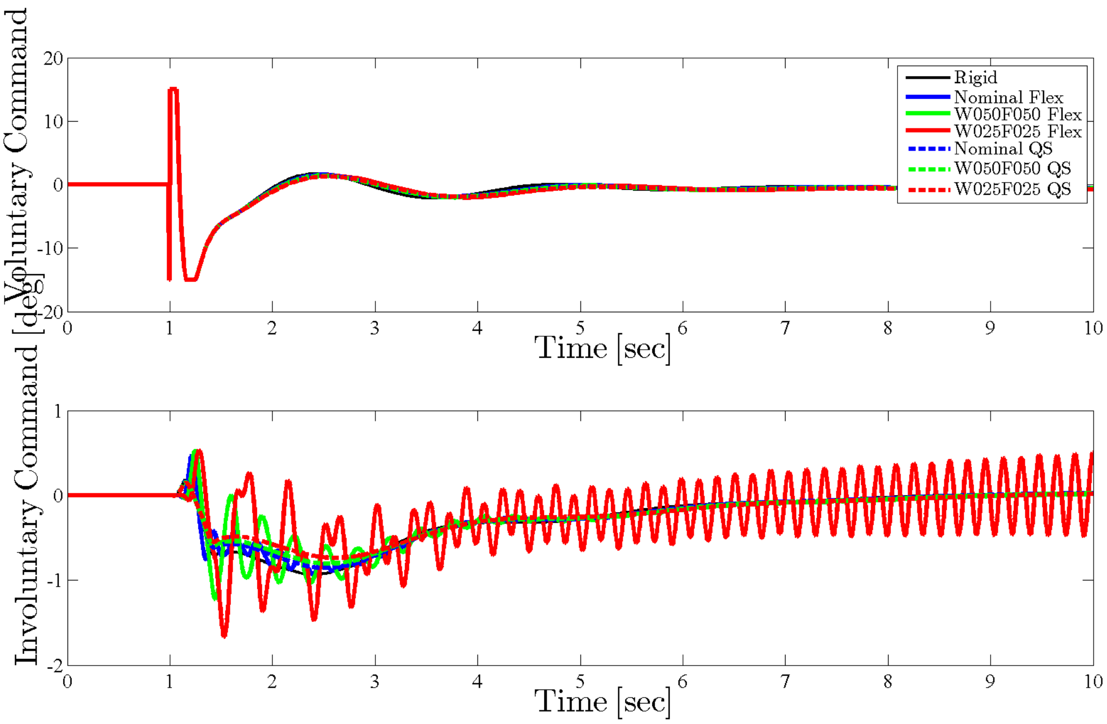

Fig. 9 Pitch capture simulation, biodynamic feedthrough model included.

5 Conclusions

This paper presented a mixed pilot model in order to allow handling qualities analysis considering also the biodynamic feedthrough effect, which is necessary for more flexible aircraft. Bandwidth versus Phase Delay and Gibson's criterion were analyzed and their results were compared to pilot-in-the-loop simulations.

While the criterion were able to predict handling qualities degradation with the increase of aircraft elasticity, both failed to predict an instability caused by the introduction of the biodynamic feedthrough model.

Since more flexible aircraft are also more susceptible to present biodynamic feedthrough coupling, it can be concluded that the frequency domain criteria used in order to predict and prevent PIO are not enough in order to assess flexible aircraft handling qualities as they are also susceptible to the PAO phenomena as well.

In order to avoid PAO occurrences, new handling qualities criteria that include the biodynamic feedthrough effect should be studied. In this context, the pilot model introduced in this paper, comprising both voluntary and involuntary commands, may be useful in the development of such new criteria.

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